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Estimation of Areal Distribution of Rain Intensities by
Radar and Rain Gauges

ESTIMATION OF AREAL DISTRIBUTION OF RAIN INTENSITIES
BY RADAR AND RAIN GAUGES

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ABSTRACT

The objectives of the work were to provide the most accurate possible radar rainfall measurements for an area of 2000 km² located in the southern part of Israel.

Transforming the radar reflectivity to rain intensity was done by the classic method of power-law Z-R, with periodical correction by the cumulative rainfall as measured by 56 integrating rain gauges. This method was preferred over the WPPM method because the radar internal calibration was found to be unstable and shifted between rain periods. Therefore a Z-R had to be established for each individual rain storm. The calibration which was done separately for two periods gave reasonable results. The ratio R/G (Radar/Gauge) daily cumulative rainfall, for the different stations averaged unity by the definition of the method, with about St. error of 20%. Radar's storm intensity analysis, for a few case studies, shows also close agreement with the ground recorder gauges. The frequency distribution as well as the intensity segment sequences were quite similar.

The temporally and spatially detailed rainfall data, provided by radar enables good analysis of rainfall-runoff events in watershed hydrology. In using radar data for hydrological purposes the scale at which the data is represented should be considered, since watershed size dominates the outlet runoff characteristics.

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INTRODUCTION

a. The importance of rainfall measurements with radar

Accurate measurements of rain intensities with good spatial and temporal resolution is important in many fields as: ecology, agriculture, civil engineering, in general, and hydrology, they all can gain substantial benefits from these measurements.

Rainfall-runoff relationships are most essential in hydrology. Information on peak discharge and storm runoff volume is cardinal for many civil engineering construction projects, such as roads, bridges, dams, reservoirs, drainage and flood control. Tillage practice and water harvesting in semi-arid regions depend critically on these relationships (Morin and Sharon, 1993).

For most hydrological purposes, rainfall is usually determined from a sparse network of rain gauges. Rain gauges sample rain fields at distinct points, and therefore do not represent accurately the spatial distribution of rainfall, especially in convective situations.

Satisfactory temporal (5 minutes) and spatial (1 km^2) resolution of rainfall is achievable, in principle, over large areas by the use of meteorological radar.

b. Deficiencies of the available radar measurement methods

a) Differences in rain drop size distribution (DSD) of different rain regimes.

The methodology of rainfall measurement with radar was based from its beginning on the theoretical relations between rain Drop Size Distribution (DSD) and the radar reflectivity factor (e.g., Marshall and Palmer, 1948). The relationship was given in the form of a power law (Eq. 1).

$$(1) \quad Z = kR^a$$

where R is the rain intensity [mm h^{-1}] and Z is the reflectivity factor [$\text{mm}^6 \text{m}^{-3}$]. Hundreds of such Z - R power law relationships were published since then, with large differences of up to a factor of 5 between rain intensities related to the same reflectivity.

b) Variations of Z_e - R due to distortion of Z .

Large differences often exist between the true reflectivity (Z) field and the radar observed reflectivity (Z_e) field, which invalidate the use of DSD based Z - R relationships without further adjustments.

There are two major sources for these differences:

1) The radar beam spreading, that convolves the radar beam pattern with the true reflectivity field (Donaldson, 1964).

2) The high frequency fluctuations of Z_e due to random interference of the echoes reflected from the individual particles (Rogers, 1971).

The effects of these two factors on Z-R relations and area integrated rainfall were shown to be significant in convective rainfall, which is characterized by large horizontal reflectivity gradients (Zawadzki, 1973; Rosenfeld et al. 1992). In agreement with this theory, Klazura (1981) has shown empirically that large radar overestimates were obtained in high rain rate gradient storms.

c) Variations with height.

Reflectivity changes with height differently for different rain types. Konrad (1978) and Szoke et al., (1986) classified cloud types by their vertical reflectivity profiles, and according to these studies, reflectivity decreases very rapidly with height in shallow tropical clouds, which produce rain mainly by warm processes. The reflectivity of deep and highly convective clouds remains constant or even increases to heights greater than the freezing level. In stratiform rainfall the reflectivity does not change much below the freezing level, and decreases rapidly above it. Due to the increasing height of the radar beam with range, each rain type has its own distinct dependence of the Z_e -R relationships on the range and on the freezing level.

Rosenfeld et al. (1992) have shown that Z_e -R relations change with range in a complex way, which greatly differs for different rain types.

d) Variation within the life cycle of a cloud

Z_e -R relationship of a cloud can significantly vary throughout its life cycle. Rain starts with a relatively few large drops, and ends with higher proportion of smaller drops. Rain starts as highly localized showers, with strong gradients, and ends as more widely scattered rain. Rain from a specific cloud may start as convective and end as stratiform, with their distinct differences of DSD. Therefore, a single Z-R relationship cannot possibly provide accurate point estimates of convective rainfall. This large, seemingly random, variability in the Z_e -R relationships has till now excluded accurate radar rainfall estimation over small areas for short duration. However, these considerations suggest that, rainfall accumulation over time/space domain, which represent the full life cycle of convective cloud can be measured accurately.

OBJECTIVES

The objectives of this work are:

- a. To develop methods and procedure for modifying the powerful weather radar remote sensing images, to obtain accurate sets of areal rainfall depth and intensities data.
- b. To evaluate watershed outlet runoff, based on the radar image information.

MATERIALS and METHODS

A- THE RADAR

Radar data for 1 Sq km. and 1 min. resolutions were obtained from E.M.S Weather radar located at Ben-Gurion air port (see map 1). The radar type is WR100-5MR with a Beamwidth of 1.6 deg., Azimuthal data resolution of 1.4 deg., pulse length of 2.0 usec, Radial resolution 1.0 km, Wave length of 5.4 cm and basescan tilt of 0.8 deg. The radar is operated in 5 minutes volumes scans mode, and 0.5 km. CAPPI are used for the analysis in this study. The radar measures reflectivity data only without a Doppler processor. Besides the fact that it is quite an old type, severe budget problems in E.M.S caused harsh reduction in the maintenance activity, resulted in lack of continuity and steadiness of the recorded data.

B- RAIN GAUGES

13 Recording rain gauges of Cassela tipping bucket type, were used in this research. These electronic gauges record, every 1 minute, how many portions of 0.1 mm rain was falling. This means that the minimum direct 1 min. measured rain intensity, is 6.0 mm/h.

The Israeli Meteorological Service provided the daily rain depth from 56 stations in the target area. The areal distribution of the recorded and daily gauges is presented in map 1.

C- METHOD OF Z-R CALCULATIONS

Two approaches were available for us to use:.

1. **The Marshal-Palmer Method.** The classic method of power-law Z-R, with a bias correction. The bias is the ratio between the radar estimated integrated rainfall, with a nominal power-law of $Z = 200R^{1.6}$, and the cumulative rainfall as measured by the daily rain gauges.
2. **The Window Probability Matching the WPMM method** (Rosenfeld et al, 1995b). This method enforces the rain intensity distribution of the radar to equal that of the rain gauges. It was developed using high quality radars in Australia and the United states, showing a better performance there.

After spending considerable amount of effort, we have realized that under the current conditions, the quality of the radar data available to us in Israel, and the small number of recording rain gauges, we prefer using the power law Z-R. The reason for that are as follows:

1. The number of recording rain gauges is only 13, as compared to 56 integrating gauges. Given that, sampling error is a major component in the accuracy of Z-R, the larger sample size of the integrating gauges dominated the accuracy of the results.
2. Due to budget cuts and lack of funding for appropriate maintenance and calibration of the radar, the radar internal calibration was shifted slightly between rain periods.

D - OUTLET RUNOFF EVALUATION

The radars' rainfall intensity was utilized for the watershed outlet runoff analysis. The method employed here was developed by Morin E. in another running research, based on her Msc. thesis (Morin E. 1996). In her work, a good agreement is shown between radar rainfall, averaged for specific time and space intervals and measured outlet runoff (Morin E. et al., 1997). Evtach watershed (43 km^2) is located in the research area, characterized by mild hills, and cultured area. A small number of rainfall-runoff events (for different years) were analyzed for Evtach catchment. It was realized that averaging radar rainfall data, over the entire catchment, for 3.5 hours intervals gives graph similar to the measured outlet runoff hydrograph. It should be stressed that although this approach is using the averaged radar data (in space and time), the detailed radar information, is needed to make the scaled averaged value as accurate as possible.

RESULTS and DISCUSSION

Cassela gauges Analysis

The Cassela rain gauge, as all other Tipping Bucket Rain Recorders types, don't present a continuous data. Fig. 1 demonstrates it for the 15/1/97 storm. As stated before, 6 mm/h is the minimum shown intensity, since the bucket gives a record only once it full with 0.1 mm of rain. Higher intensities, as presented in the data, are always multiplication of six. The natural rain does not have such characteristics. It is a continuum of various intensities. The calculated line, presents therefore, much closer intensities to those of nature. The calculation were done on the assumption that the rain falls in continuous rates in between the pulses, so the actual data intensities have to be divided by the time gapes between the pulses. As demonstrated in Fig.1, the accumulated depth lines are the same for the data and the calculated rain.

All 1996/7 rain storms were analyzed for the 13 stations. This information was the basis to validate the radar rates.

Radar Calibration

The reflectivity values were transformed to rainfall intensities by the method of power law and bias correction for each storm (Wilson & Brandes, 1979).

A power law is applied to the radar reflectivity data (Z) to get intensity value (R):

$$(2) \quad Z = 200R^{1.6}$$

The initial intensity maps are integrated for the storm period. Storm's depth at locations of rain gauges is compared with measured rain's depth by these gauges. For each storm, a bias correction factor is derived which is an average of the ratio G/R (Gauge rain depth/Radar rain depth) for each rain gauge location. The intensities are multiplied by the factor, and the result presents the final intensity maps.

Comparison Between Rain Gauges and Radar Rain

A. Daily rain depth

Tables 1&2 present the gauge's and radar's rain depth differences as well as the G/R ratio for the storms of 15-16 Jan. and 21-23 Feb. 1997 respectively. For few of the 56 stations presented, the stations data is uncertain (it's marked by asterisk in the tables). The average rain depth in the region for the January storm was 46 mm, with St. error of 19% for the individual stations G/R biases. The average rain depth for the February storm was 80 mm and the stations G/R biases St. error was 35%. For all the stations in the study area, Maps 2&3 present those differences, in percentage,. There is obvious bias, for the stations along the coast line, that show higher surplus of the radar estimates. The average radar depth for the January storm, along the coast line, is 27% higher in comparison to the ground gauges', in February it is even higher, coming to 64% differences.

Regression analysis, between the radar and the 56 gauges rain depth, as shown in Figs. 2&3, demonstrate the scatter shape of the radar fitness to the measured data. Correlation coefficients r^2 of 0.54 and St. error of 7.6 mm (16%) were calculated for the Jan. storm. For February storm, r^2 of 0.89 and St. error of 14.3 mm (18%), are shown in the figures. Fig. 4 presents the daily rain depth cumulative frequency of the Radar and the stations gauges. For both, the January and February storms, there is quite good similarity in their cumulative frequency distributions.

B. Storms Rain Intensities

Negba station, which is located in the Evtach watershed (see Maps 2 and 3), was chosen for the evaluation and comparison of the rain intensities of the radar and Cassela rain gauge. Figs 5&6 (a;b;c) present this comparison for January 15-16 and February 21-23 storms. The time analyzed was from 8 am to 8 am For the two periods. Fig.7 (a;b;c;d) show the rain intensities frequency distribution of these two storms. Since the radar analysis represents scale equivalent to running averages of 3 min. the Cassela intensities are shown by their 3 minute running averages too. Figs. 5;6;7 demonstrate reasonable agreement between of the radar rates and values of the Ground Cassela gauge. We have to stress here again that radar evaluates 1 km^2 rain while the gauge measured the rain on 400 cm^2 only.

Watershed Outlet Runoff

The calibrated radar rainfall data were used for runoff analysis in Evtach watershed for the rainfall-runoff event dated 22-25/Feb./1997. The basic data for the analysis were rainfall maps, of 5 minutes intervals, for each 1 km^2 of the watershed area. Fig. 8 is an example for the 5 min. interval map while Fig 9. presents the accumulated rainfall of Feb. storm. All this detailed rainfall data was averaged over the Evtach watershed, for few time intervals. The averaged radar's rainfall storm was compared to the measured outlet runoff as well as to the rain gauge rainfall data in Negba and Nitzanim. Fig. 10 show this analysis for time interval of 5 minutes (original radar measurement interval). It can be seen, in this figure that the 5 minutes rainfall varied considerably from the outlet runoff. Fig. 10 show also, large differences between the point rainfall and the catchment averaged rainfall. The 1 hour interval rainfall graphs (Fig. 11) are smoother, but still, altered each other and from the runoff graph. Both the radar and Negba, 3.5 hours running average interval rainfall graph, have a pattern similar to the outlet runoff graph (Fig. 12). Rainfall presents at this scale needs simpler manipulation (hydrological model) for transforming it to outlet runoff. Demonstration here that averaged radar's data are good indicator of the outlet runoff, does not mean that rain gauge data could give the same results. All three time intervals (5 minutes, 1 hour, and 3.5 hour) show that, rainfall sampled at Nitzanim, does not represent well the catchment averaged rainfall. Using this data as rainfall input in hydrological model might lead to inappropriate results.

The analysis presented here demonstrate two important issues :

1. The temporally and spatially detailed rainfall data provided by radar enables much better analysis of rainfall-runoff events than the point gauge rainfall.

- 2. In using radar data for hydrological purposes the scale at which the data are represented should be considered. For outlet runoff of Evtach watershed (43 km^2), it is suggested here that the radar data could be averaged over the entire basin and in 3.5 hours intervals. For other purposes different scale may be appropriate.

CONCLUSIONS

The objectives of the work were to provide the most accurate possible radar rainfall measurements of the area of interest and to applied it for practical hydrology. Two approaches were available to us for use:

1. The classic method of power-law Z-R, with periodical correction by the cumulative rainfall as measured by integrating rain gauges.
2. The Window Probability Matching Method (WPMM). The method enforces the rain intensity distribution of the radar to equal that of the rain gauges. This method requires that:
a) the rain gauges will be recording the one minute intensities. b) a minimum of 200 mm of rain coming from a steady factors in the calibration of the radar images.

The number of recording rain gauges was only 13, as compared to 56 integrating gauges. Given that the sampling error was a major component in the accuracy of Z-R, the mere larger sample size of the integrating gauges dominated the accuracy of the results. Due to lack of appropriate maintenance, the radar internal calibration was shifted slightly between rain periods. Therefore a Z-R had to be established for each rain storm separately. That also made the sample size a dominant factor in the selection of the power-law method. After spending considerable amount of time and effort, we realized that the quality of the radar data available to us in Israel, and the small number of recording rain gauges, compromise this approach. We found that using the power law Z-R is preferable under the current conditions.

The calibration which was done separately for two periods gave reasonable results. The ratio R/G (Radar/Gauge) for the different stations averaged unity with about St. error of 20%. The higher radar's rain depth, along the sea, in comparison to the gauges on the ground was quite reasonable. This systematic differences is consistent with the observations that the convective rain clouds become more mature, on the average, as they move from the coast line inland.

This change is associated with systematic change in the Ze- R relationship (Rosenfeld 1986).

The WPMM is, in principle, able to take such effects into account, and will hopefully be applied in the future. Radar's storm intensity analysis, for a few case study, shows also

reasonable agreement with the gauges. The frequency distribution as well as the intensity segment sequences were quite similar.

Watershed Hydrology gains, by the rain detailed information, a very powerful tool for better analysis, in spite of the actual radar images problems. The detailed rain information can and should be analyzed for the appropriate scale, correlating with the integrated watershed runoff, in simple ways but with high accuracy.

As a result of our methodological investigation, we see that, for future radar - rainfall research, a combination of the two methods, have the potential use of both methods without their disadvantages. We recommend that in future studies we will try the following:

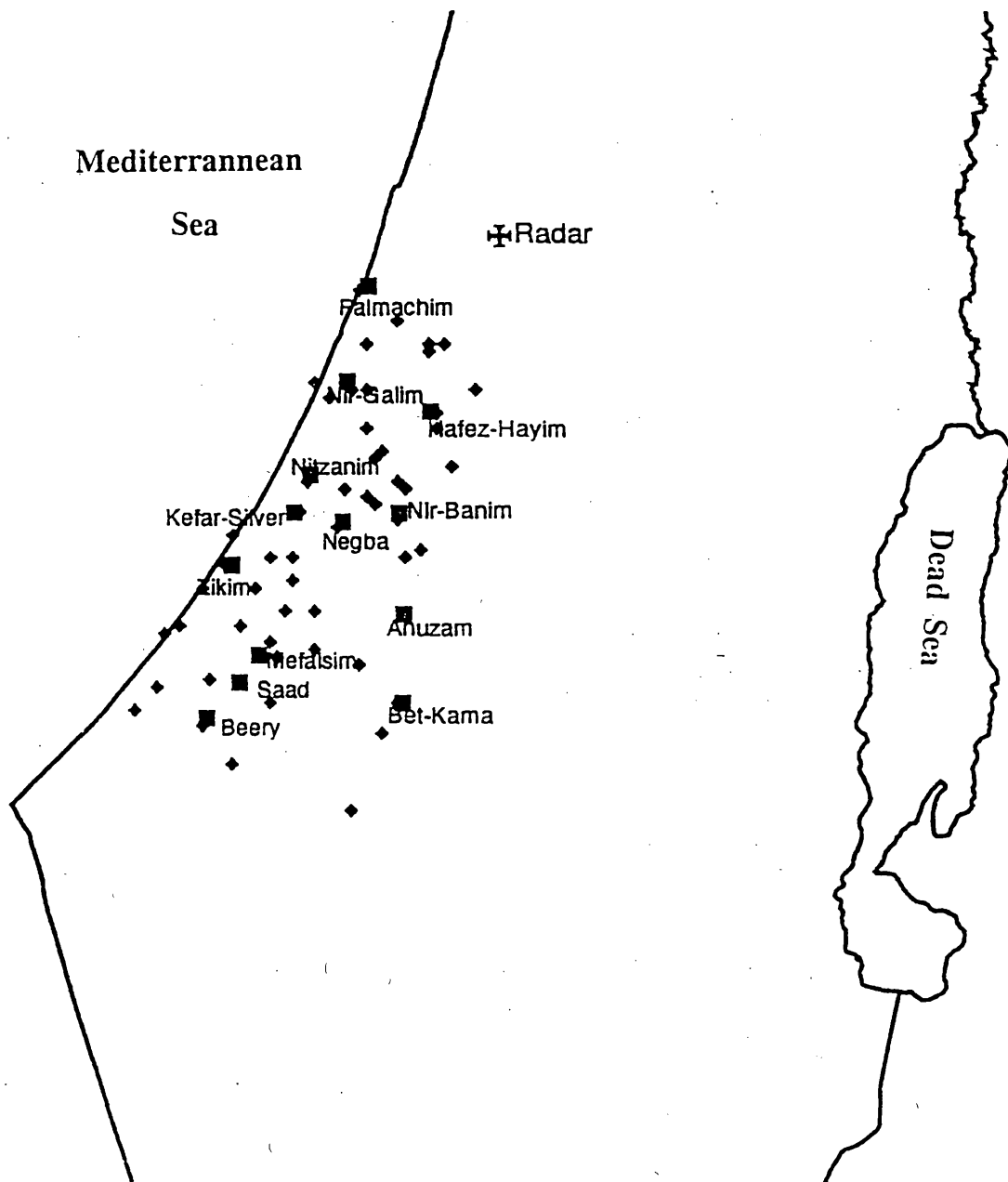
Establishing first a PMM Z-R relation using the full data set available, from all historical data and then applying to it the bias correction on a storm by storm basis.

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Map 1

Cassela rain gauges and daily rain gauges used for radar calibration

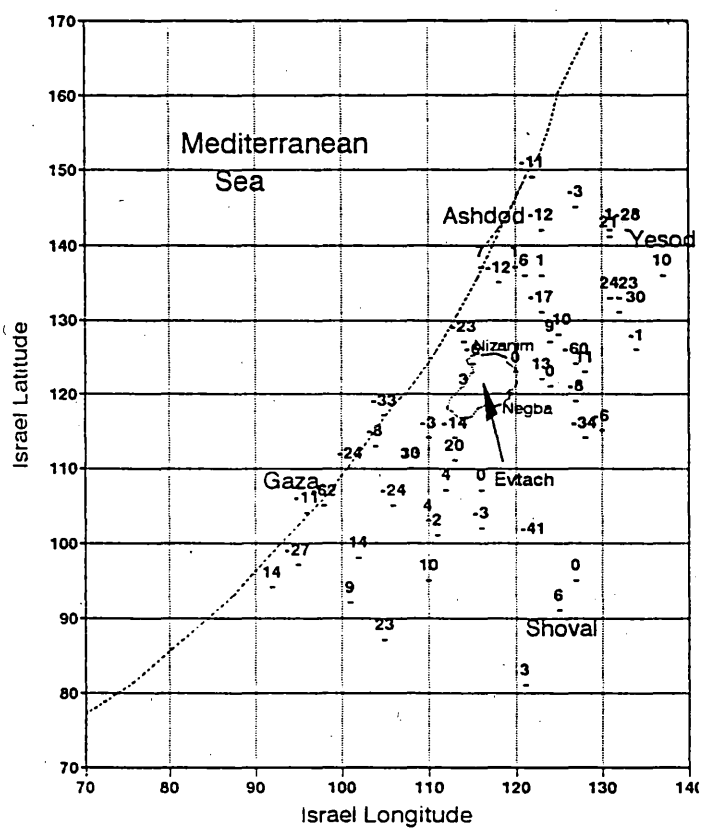


0 10 20 30 40 Kilometers

- Cassela rain gauge
- ◆ Daily rain gauge

Map 2

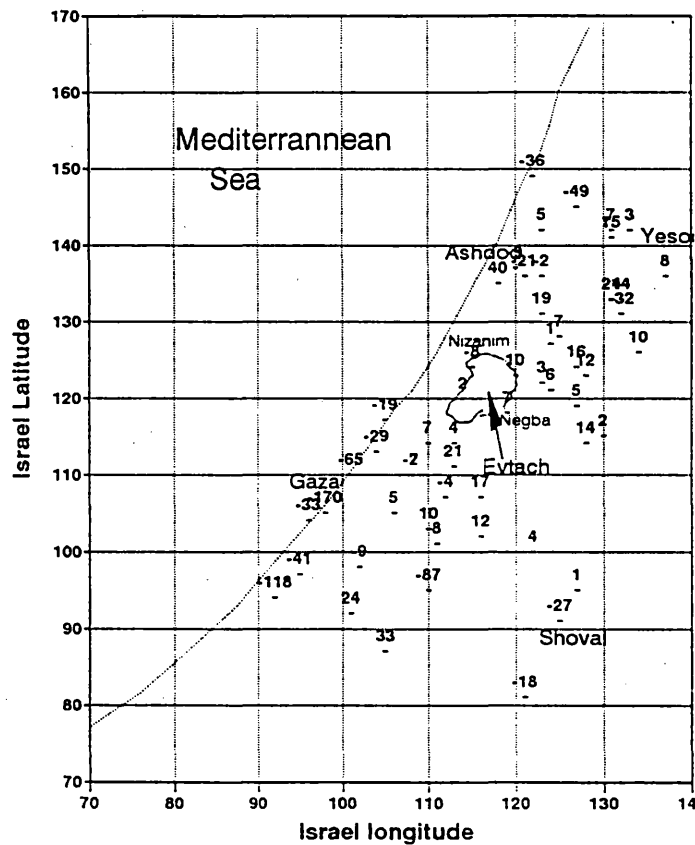
RAIN DEPTH DIFFERENCES IN PERCENTAGE
GAUGES-RADAR(PAL.) FOR 15-16 Jan.1997



qq	Radar	Gauge	r/g	%(g-r)/g
SUM& AVG.	2634.5	2632.7	1.0	0.0
Std.Error	11.0	12.4	0.2	19.5
Averag	46	46	1	-3

Map 3

RAIN DEPTH DIFFERENCES IN PERCENTAGE
GAUGES-RADAR(PAL.) for 21-23 Feb. 1997



	Radar	Gauge	r/g	%(g-r)/g
SUM&AVG.	4334.6	4465.7	1.1	2.0
St.Error	41.6	47.9	0.4	35.4
Avereg	79	81	1	-7

Table 2

RAIN DEPTH DIFFERENCES BETWEEN GAUGES AND RADAR
PALMER METHOD- FOR THE DAY OF 21-23 Feb. 1997

Factor: 6.88

Station	Long	Lat.	radar	gauge	r/g	% Diff.
Nuzitat*	92	94	36.1	16.5	2.2	-116
Nir-Gaza*	95	97	31.5	22.2	1.4	-41
Gaza	96	104	26.5	19.8	1.3	-33
El-Shaty*	98	105	28.9	10.7	2.7	-170
Bet-Lahya*	101	110	40.5	24.5	1.7	-65
BEERI	101	92	23.4	30.9	0.8	24
Nacal-Oz	102	98	34.0	31.1	1.1	-9
Zikim	104	113	58.9	45.5	1.3	-29
Ashkelon	105	127	93.4	78.0	1.2	-19
Saad	105	87	21.1	31.6	0.7	33
Bet-Hanun	106	105	37.9	40.0	0.9	5
Mefalsim	108	110	42.7	41.9	1.0	-2
Yad-Mordec	108	110	42.7	39.6	1.1	-7
Mavkyim	110	114	71.0	76.5	0.9	7
Nir-Am	110	103	37.8	42.5	0.9	10
Tkuma	110	95	28.1	15.0	1.9	-67
Gevim	111	101	35.5	39.0	0.9	8
Or-Haner	112	107	47.3	45.1	1.0	-4
Talmy_yafe	113	114	88.6	92.4	1.0	4
Gvar-Am	113	111	46.5	58.9	0.8	21
K.Silver	114	120	138.5	142.0	1.0	2
Nizanim	115	124	135.8	124.9	1.1	-6
Bror-Hayil	116	107	43.4	52.7	0.8	17
Dorot	116	102	29.7	33.9	0.9	12
Ashdod-(Ag.	118	135	99.0	167.0	0.6	40
Negba	119	118	149.9	161.4	0.9	7
Nir-Galim	120	137	89.2	81.4	1.1	-9
Masuot_ltz.	120	123	126.3	140.8	0.9	10
Bney-Darom	121	136	107.2	88.4	1.2	-21
Eshel-Hn	121	81	14.4	12.2	1.2	-16
Palmachim	122	149	80.8	59.2	1.4	-36
Ruhama	122	100	26.0	27.1	1.0	4
Chavatzelet	123	142	99.6	105.3	0.9	5
Yavne-(Kv.)	123	136	101.7	98.9	1.0	-2
Hatzor-Ashd	123	131	118.9	147.3	0.8	19
Eyn-Zurim	123	122	133.9	138.2	1.0	3
Ber-Tuvya	124	127	141.0	142.5	1.0	1
Shafir	124	121	128.8	138.5	0.9	6
Orot	125	128	142.7	154.8	0.9	7
Shoval	125	91	25.5	20.0	1.3	-27
Yavne(Sh.)*	127	145	123.2	82.3	1.5	-49
Timurim	127	124	109.0	131.0	0.8	16
Nir-Banim	127	119	135.8	143.1	0.9	5
Bet-Kama	127	95	24.6	25.0	1.0	1
Kedma	128	123	108.2	123.2	0.9	12
Mivcor	128	114	99.7	117.0	0.9	14
Gat	130	115	102.4	105.5	1.0	2
Gan-Shlomo	131	142	87.9	95.4	0.9	7
Givat-Brener	131	141	81.2	96.0	0.8	15
Hefetz-Hay	131	133	110.8	147.1	0.8	24
Bet-Chilkia	132	133	119.8	140.3	0.9	14
Revadym	132	131	127.1	96.0	1.3	-32
Kfar-Bylu	133	142	97.1	100.9	1.0	3
Kfar-Menac	134	126	112.7	126.3	0.9	10
Yesodot	137	136	90.0	98.4	0.9	8

* Unsure Stations

	Radar	Gauge	r/g	% Diff.
SUM & AV	4334.6	4465.7	1.1	2.0
St.Error	41.6	47.9	0.4	35.4
Avereg	79	81	1	-7

Fig. 1

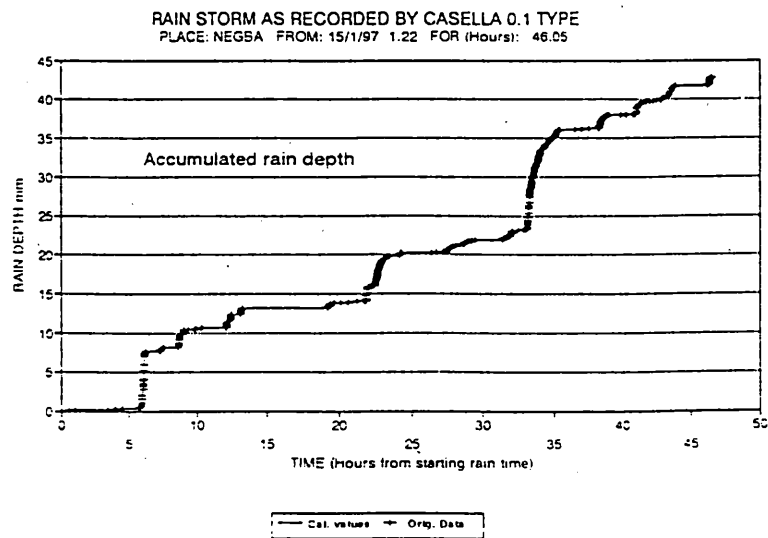
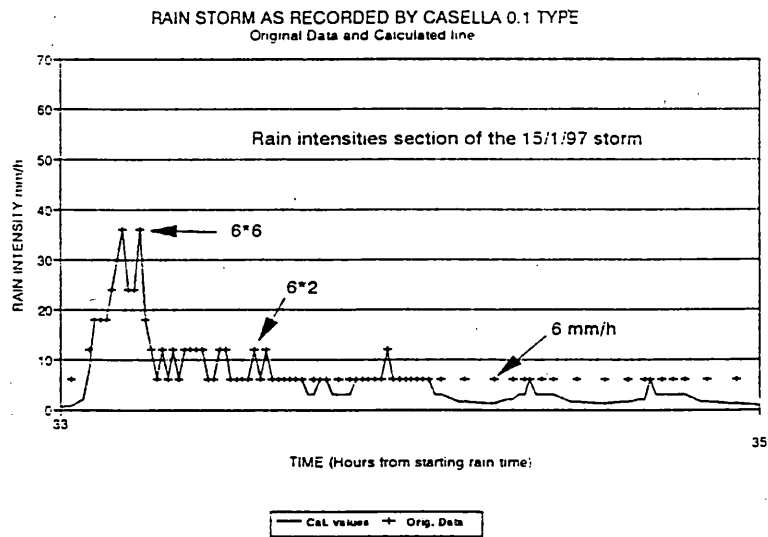
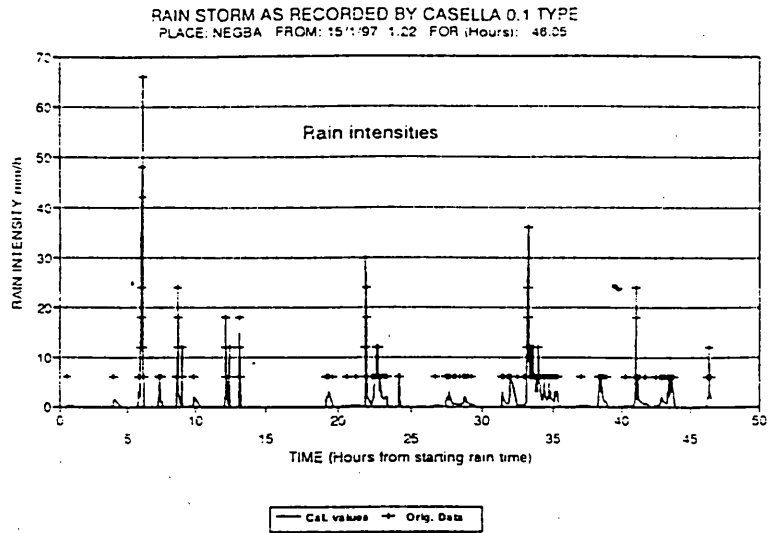


Fig. 2

Gauges rain depth in comperison to the radar rain depth
Storm of 15-16 Jan. 1997 (Palmer Method)

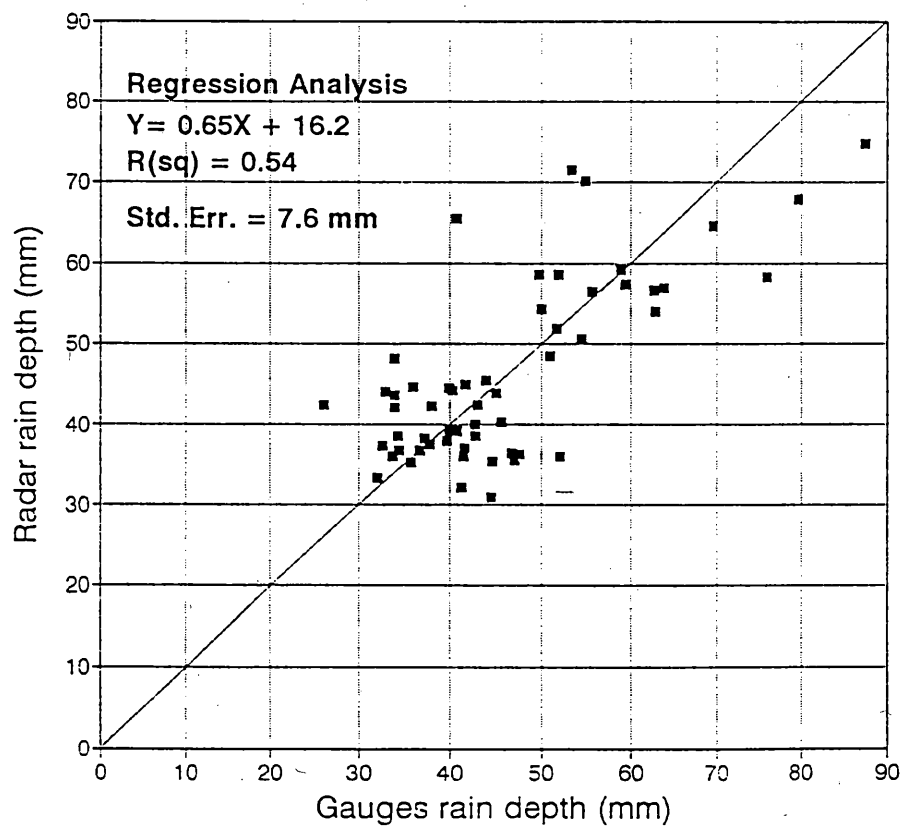


Fig. 3

Gauges rain depth in comperison to the radar rain dep
Storm of 21-23 Feb. 1997 (Palmer Method)

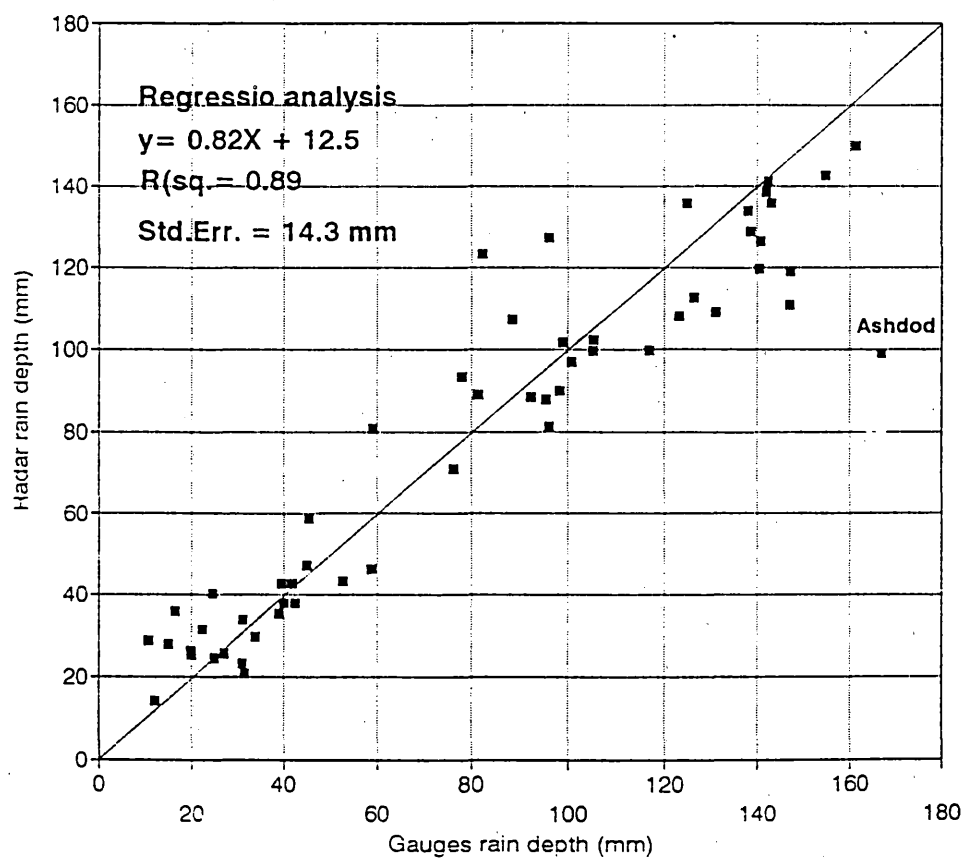


Fig. 4

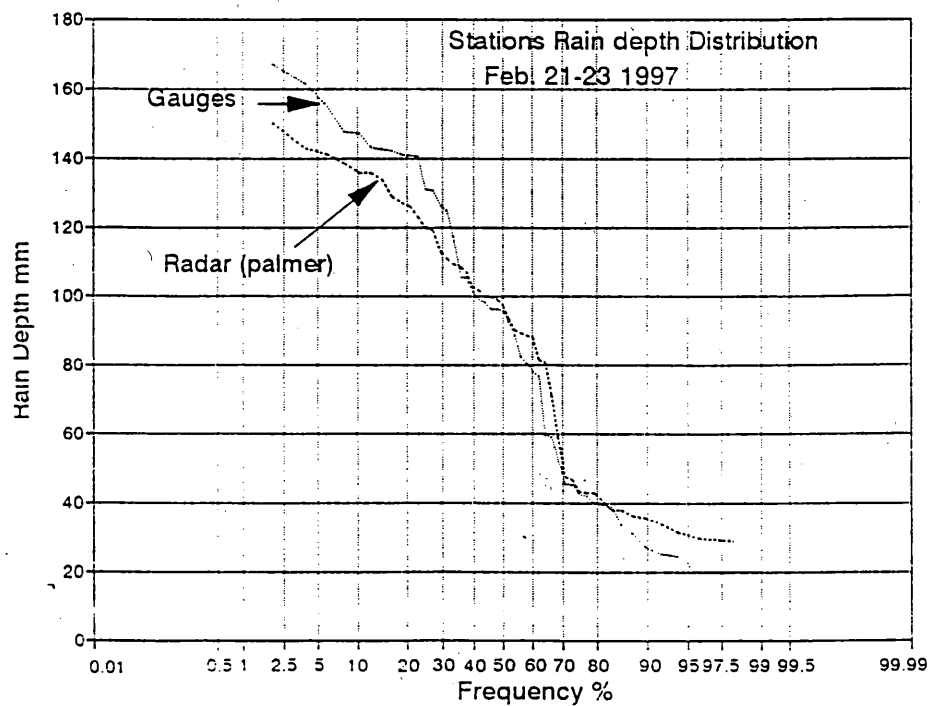
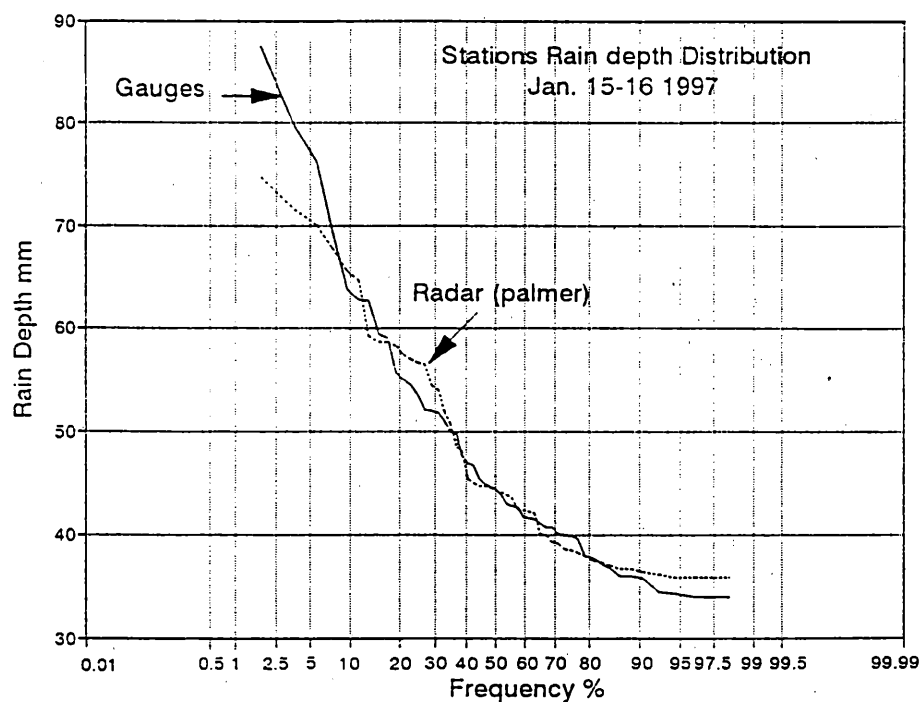


Fig. 5

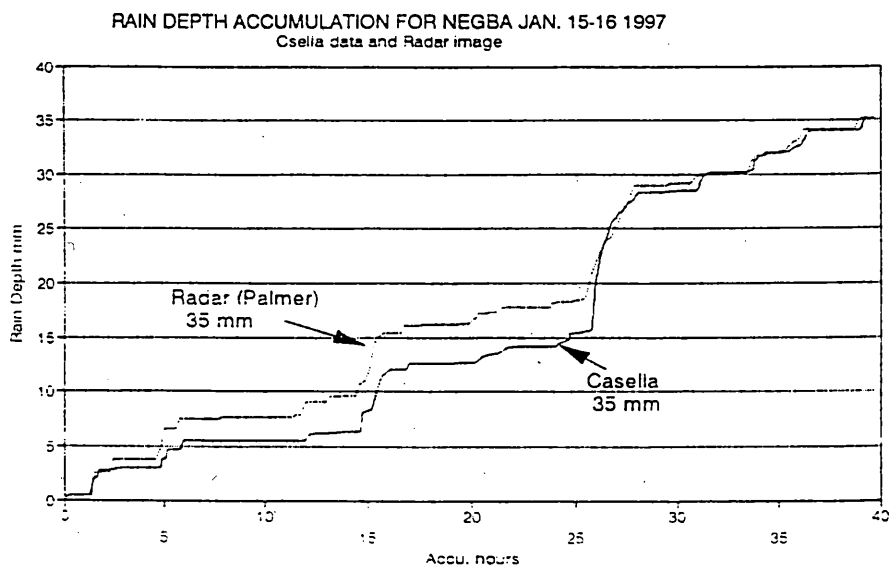
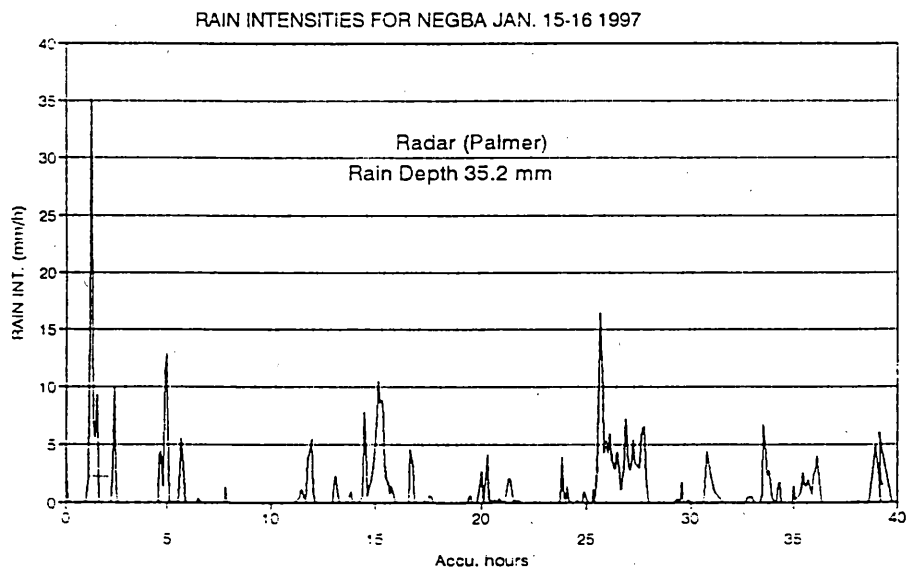
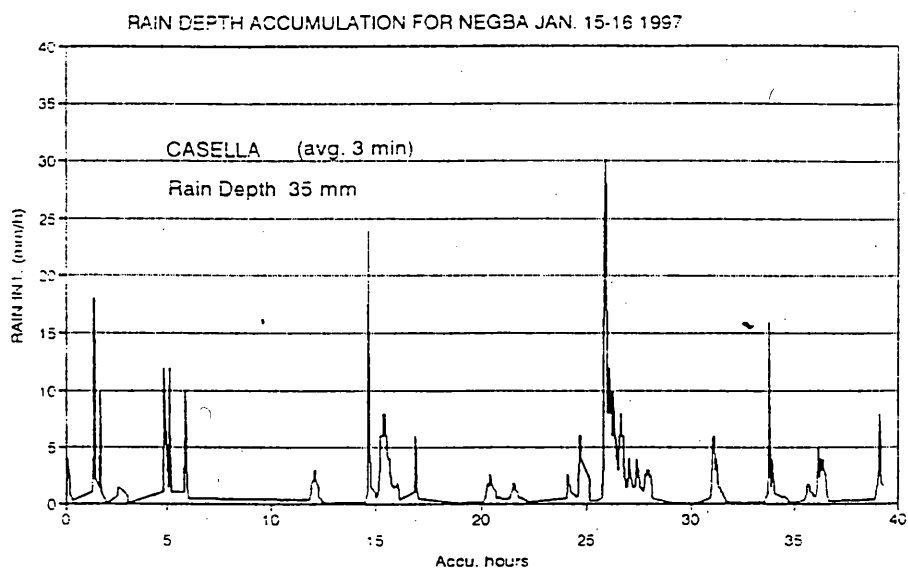


Fig. 6

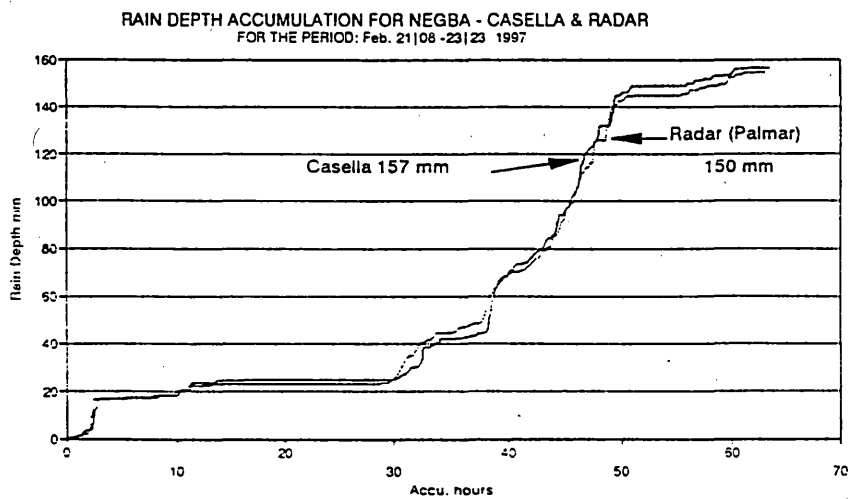
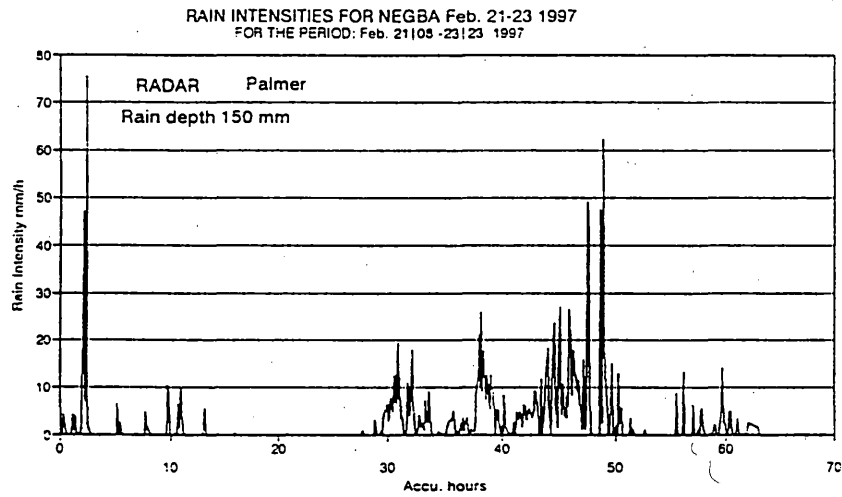
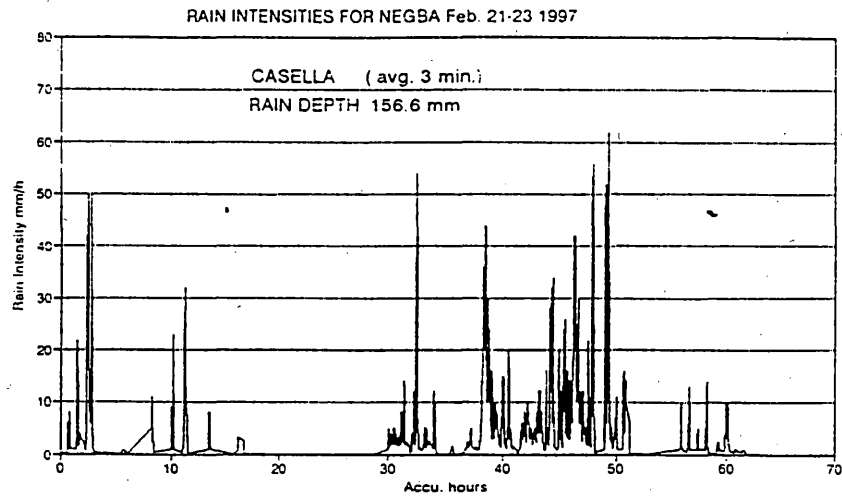


Fig. 7

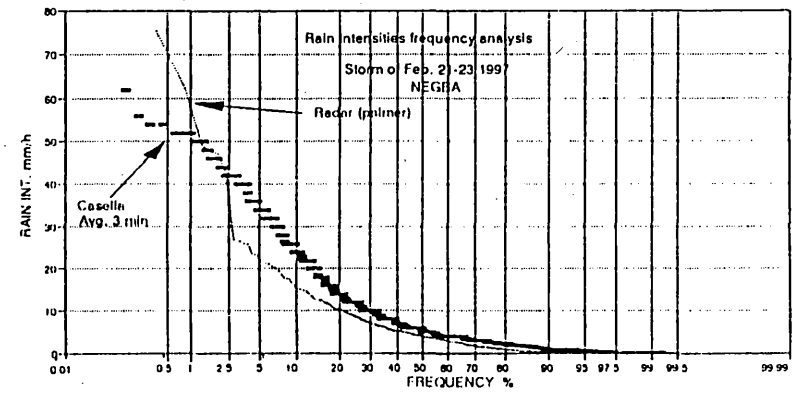
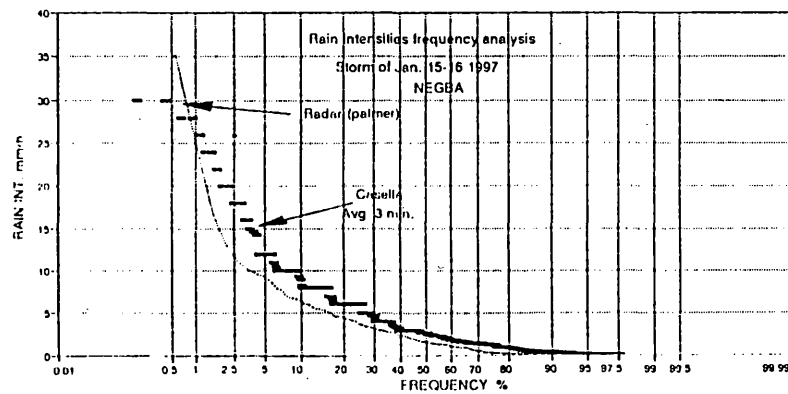
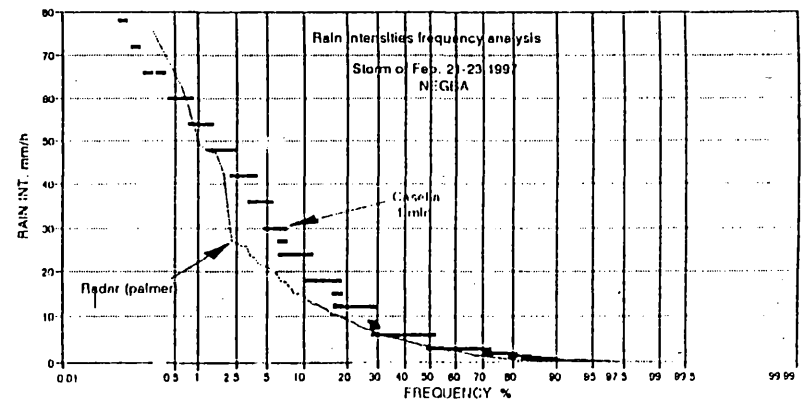
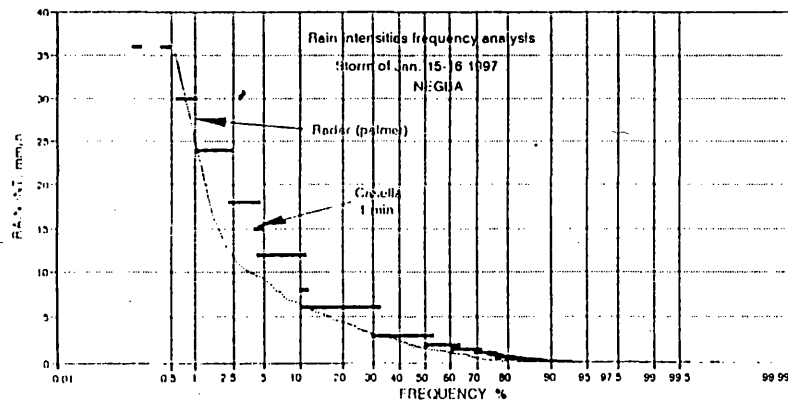


Fig. 8

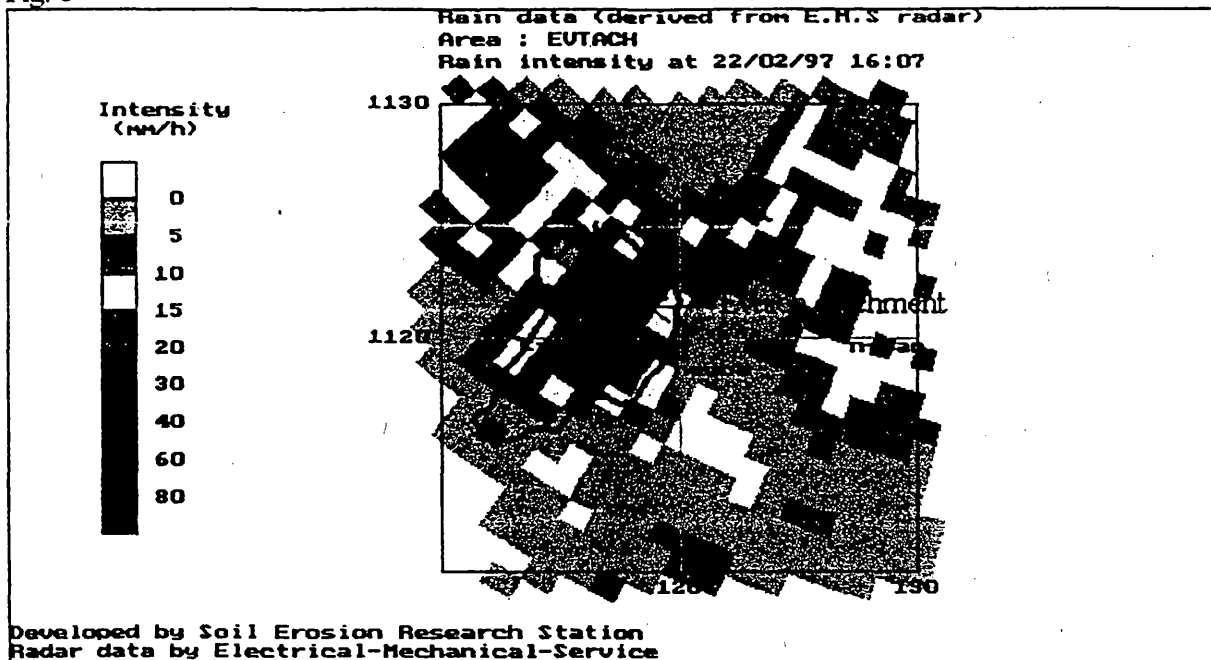


Fig. 9

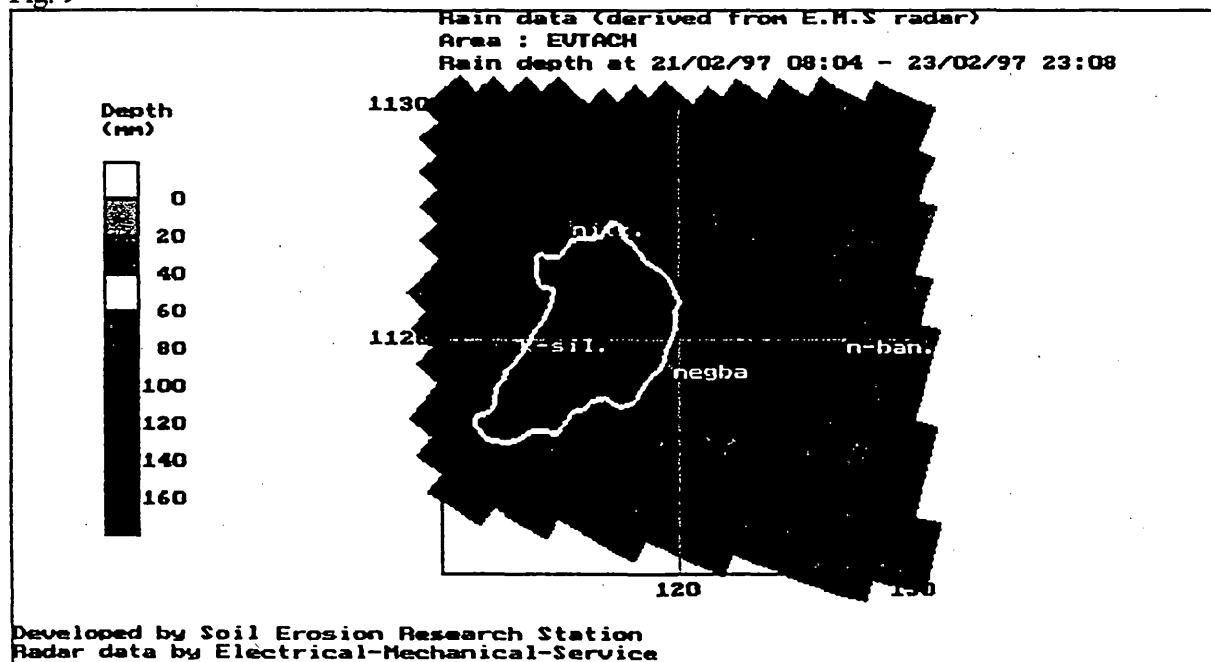


Fig. 10

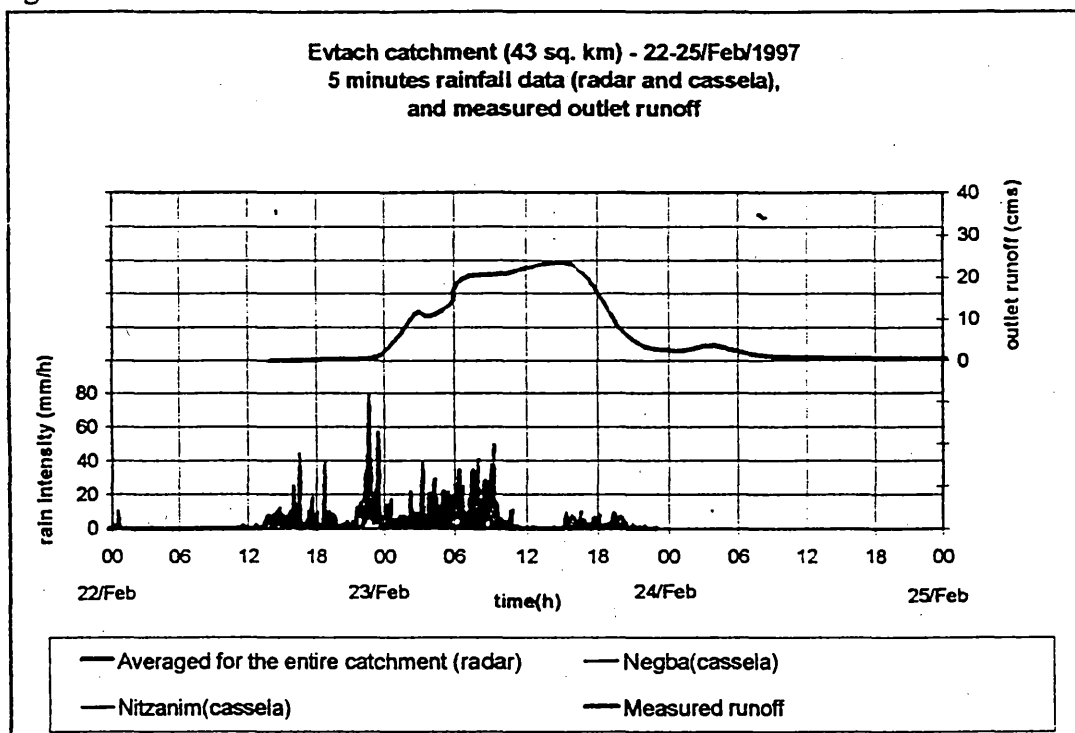


Fig. 11

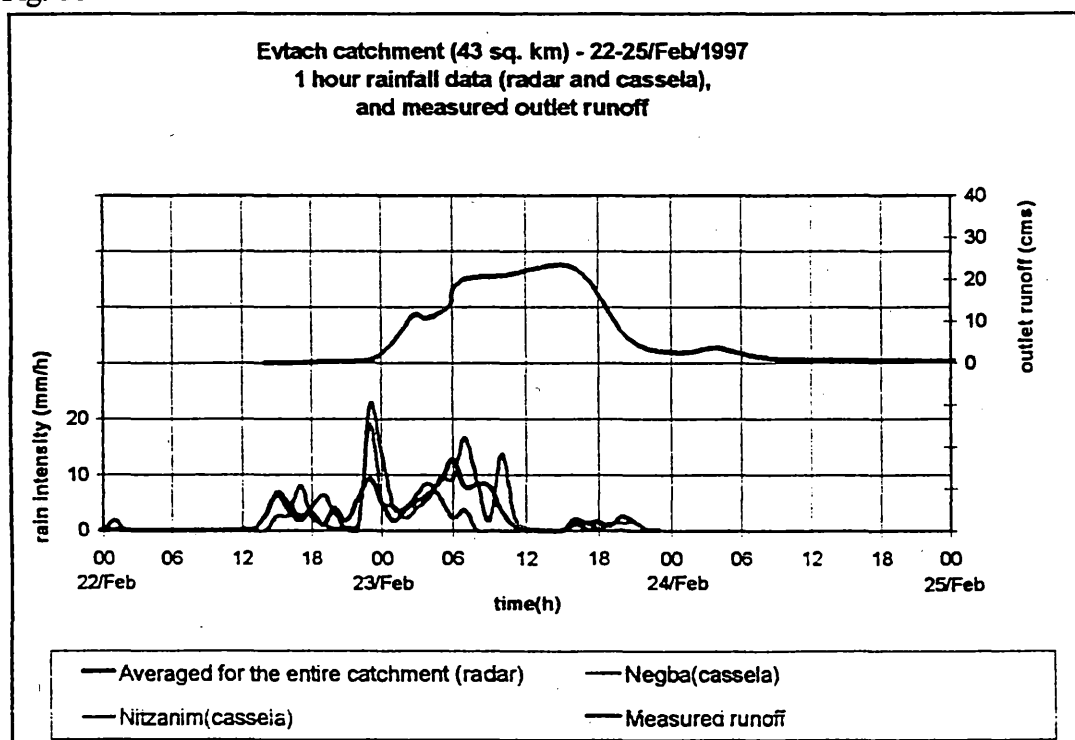


Fig. 12

